



# Mountain Fen Distribution, Types and Restoration Priorities, San Juan Mountains, Colorado, USA

Rod A. Chimner · Joanna M. Lemly · David J. Cooper

Received: 27 October 2009 / Accepted: 29 March 2010 / Published online: 25 April 2010  
© Society of Wetland Scientists 2010

**Abstract** Mountain fens are vital ecosystems for habitat, biodiversity, water and carbon cycling, but there is little comprehensive information on their distribution, abundance or condition in any region of the western U.S. Our study objectives were to: 1) evaluate fen distribution, abundance and characteristics in the San Juan Mountains of Colorado, 2) quantify disturbances, and 3) prioritize restoration needs of fens. We mapped 624 fens in 37 watersheds and collected field data on 182 of these fens. We estimated that approximately 2,000 fens occur in the San Juan Mountains, primarily in the subalpine zone at an average elevation of 3,288 m. Fens ranged from 0.2 to 20.5 ha in size, peat thickness ranged between 0.40 to >4.00 m, and surface slope ranged from 0–21%. Groundwater pH ranged from 3.1–7.6 and  $\text{Ca}^{+2}$  from 1–341 mg/L, reflecting the diverse geochemistry of watershed parent materials. We identified 188 vascular and 63 bryophyte taxa, and classified the 309 sampled stands into 20 plant communities that formed along complex hydrogeomorphic and geochemical gradients. The majority of fens were in excellent condition;

however 10% of our sampled fens had high to very high restoration potential due to impacts from roads, mining, and ditching.

**Keywords** Disturbances · Fens · Peatlands · Restoration · Vegetation

## Introduction

Mountainous regions cover nearly a quarter of the earth's land area and, although they house only 10% of the world's population, are heavily utilized for forestry, livestock grazing, energy and mineral production, and recreation (Millennium Ecosystem Assessment 2005). Mountain ranges are also globally important for carbon storage and water cycling (Viviroli et al. 2003; Schimel and Braswell 2005). Many of the world's major rivers originate in mountains because of high precipitation rates from orographic lifting. These processes support a high density of rivers and a vast array of wetlands, including riparian areas, wet meadows, and marshes (Cooper and Andrus 1994; Gerdol 1995; Clausen et al. 2006; Chimner et al. 2007). Among mountain wetlands, peatlands can be the most abundant type in many high-elevation regions (Cooper and Andrus 1994).

In the southern Rocky Mountains of the United States, all peatlands are classified as fens, supported by groundwater input and not solely by direct precipitation (Cooper and Andrus 1994). These fens are often areas of high biodiversity and are regionally important refugia for rare plant and animal species that are otherwise limited to colder environments of boreal and arctic regions (Cooper 1996). Species such as Altai cottongrass (*Eriophorum altaicum*), buckbean (*Menyanthes trifoliata*), purple cinquefoil (*Comarum palustre*), and *Sphagnum balticum* occur within the

**Electronic supplementary material** The online version of this article (doi:10.1007/s13157-010-0039-5) contains supplementary material, which is available to authorised users.

R. A. Chimner (✉)  
School of Forest Resources and Environmental Sciences,  
Michigan Technological University,  
1400 Townsend Drive,  
Houghton, MI 49931, USA  
e-mail: rchimner@mtu.edu

J. M. Lemly · D. J. Cooper  
Department of Forest, Rangeland and Watershed Stewardship,  
Colorado State University,  
Fort Collins, CO 80523, USA

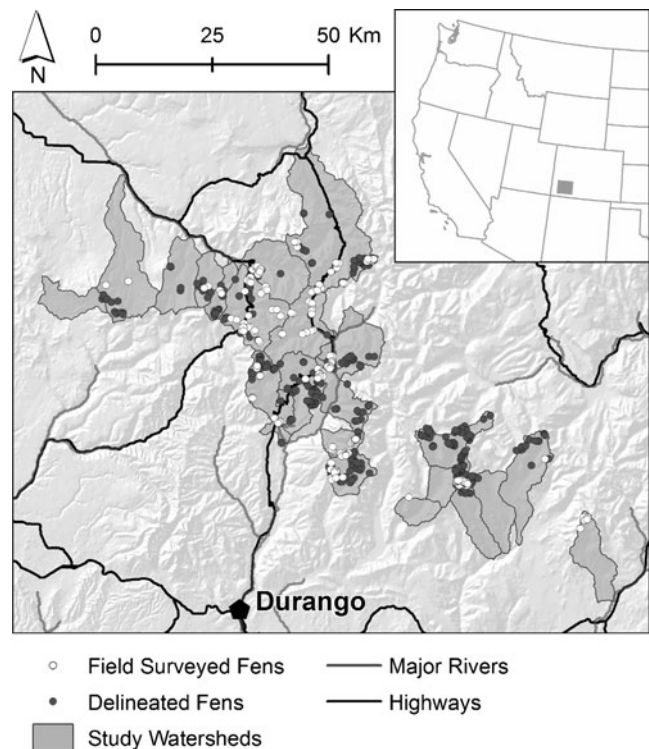
southern Rocky Mountains, disjunct by hundreds or thousands of km from their main ranges in boreal North America (Cooper et al. 2002; Weber 2003). Rocky Mountain peatlands also provide important habitat for elk (*Cervus elaphus*), moose (*Alces alces*), and many species of amphibians and migratory birds.

Mountain fens have long been altered by human activities, but little information exists on the types of impacts that have occurred and the proportion of fens in need of restoration. Disturbances may reverse the 10,000+ year old process of peat accumulation (Chimner and Cooper 2002) and lead to peatland destruction in many areas (Cooper et al. 1998; Chimner and Cooper 2003a; b; Patterson and Cooper 2007). Common anthropogenic disturbances that have been noted in western North American fens include hard rock and gravel mining, water reservoir construction, irrigation diversions for agricultural water use, trans-basin water diversions, road construction, timber and energy development, livestock grazing, housing and ski area development, and recreation (Cooper and Wolf 2006; Patterson and Cooper 2007; Zier and Baker 2006). Despite the ecological and hydrologic importance of mountain fens, there is little comprehensive information on their distribution, abundance, aerial extent, and type in any region of North America. Because many fens lack navigable waters, they may have little or no federal, state, or local protection and are often overlooked in large-scale wetland and watershed protection programs (Tiner et al. 2002). Our objectives were to: 1) determine the distribution, abundance, and characteristics of fens, 2) document the range of disturbances to fens, and 3) prioritize restoration needs for fens in the San Juan Mountains in southern Colorado.

## Methods

### Study Area

The San Juan Mountains (Fig. 1) are geologically complex, with a core of Precambrian crystalline rocks, localized areas of volcanism and intrusive igneous rock, and sedimentary rocks along the range margins. Large areas of unsorted Quaternary deposits of glacial, colluvial, and alluvial origin occur in valleys and on hillslopes (Winters et al. 2003). The San Juan Mountains are the highest elevation range of the entire Rocky Mountain system, with 14 peaks reaching over 4,270 m elevation, and hundreds of peaks over 3,660 m. Glaciated high elevation valleys have broad U-shapes with numerous tarns, cirques, and moraines, while narrow lower elevation valleys have been cut by rivers. Higher elevation areas have snowmelt driven hydrologic regimes, and lower elevations are rainfall driven (Winters et al. 2003).



**Fig. 1** Randomly selected watersheds (grey polygons), mapped fens (black circles), and visited fens (open circles) in the San Juan Mountains, Colorado

### Fen Identification and Mapping

We used natural color aerial photograph stereo pairs and digital aerial imagery to identify wetlands with brownish colors and peat generated landforms typical of fens in our region. We mapped and field verified fens in 11 adjacent watersheds in two Colorado counties (San Miguel and Ouray) to perfect methods for fen identification. We then mapped and visited fens in randomly selected watersheds across the entire mountain range, which covers 44,194 km<sup>2</sup>. We used the National Hierarchical Framework of Aquatic Ecological Units in North America (Maxwell et al. 1995) and the National Watershed Boundary Data sets Federal Standards for Delineation of Hydrologic Unit Boundaries to identify HUB 6<sup>th</sup> level watersheds. We developed a watershed classification using agglomerative cluster analysis based upon the percent of each bedrock type (calcareous, intrusive igneous, and volcanic), elevation categories, and climate in each watershed (Winters et al. 2003; Wohl et al. 2007). A total of nine watershed types were identified, and two watersheds of each type were randomly selected for inventory. We also added nine additional HUB 6<sup>th</sup> level watersheds with unique geological characteristics. Within each watershed, the boundary of each fen was delineated with the GIS software package ArcView 9.2 (ESRI 2006). We field verified our image interpretation by investigating

soils and hydrologic regime, and corrected fen polygon boundaries. We determined the ownership, elevation, and exact location of each fen from available GIS layers.

### Field Assessments

In many watersheds, all mapped fens were field verified and sampled. In watersheds with large numbers of fen polygons, we visited a subsample by selecting only a few from areas with large clusters of similar fen types. Subsamples were chosen to maximize the diversity of fens sampled and to not oversample areas with large numbers of fens. A total of 182 fens were field sampled during June–August 2006 and 2007. We defined fens as wetlands with organic soils at least 40 cm thick and used the Natural Resources Conservation Service's Soil Taxonomy to identify organic soils (Soil Survey Staff 2006). In all field verified fens, we determined location and ownership, overall site characteristics, condition and disturbances, and collected stand-level vegetation composition data. All data were entered into a Palm Pilot® using the software program EcoNab (NISS 2006). Data were downloaded each day into Microsoft Access® creating an easily accessible electronic database.

In each study fen, homogenous stands (usually between 1–5 stands per fen) of vegetation were identified and data were collected within these stands. A 40-cm deep pit was opened with a shovel in each stand, the pH and temperature of groundwater that filled the hole was measured using an YSI 100 handheld pH meter, and water table depth was recorded once it equilibrated. One ground water sample was collected from each fen, stored in a 20-ml scintillation vial, sealed immediately, and kept refrigerated until analyzed by the U.S. Forest Service, Grand Rapids, Minnesota, for major anion and cation concentrations. A soil sample from 30–40 cm depth was collected from each site for analysis of percent organic matter content by loss on ignition (Belyea and Warner 1996). The approximate thickness of the peat body was measured using a tile probe and the level of peat decomposition was determined with the von Post scale (Rydin and Jeglum 2006). Percent slope was measured with a clinometer and each fen was placed into a hydrogeomorphic class of either sloping or depression (Brinson 1993).

Vegetation composition within each stand was analyzed using the relevé method (Mueller-Dombois and Ellenberg 1974). The canopy cover of each vascular plant and bryophyte species was visually estimated and voucher specimens of any unknown species were collected. *Sphagnum* spp. were identified by Richard Andrus (Binghamton University, New York, BING) and all other mosses by William Weber (University of Colorado, Boulder, COLO), where vouchers were deposited. Taxonomy from the Flora of Western Colorado was followed (Weber and Wittmann 2001).

Vegetation data from homogenous stands were classified using agglomerative cluster analysis with Sørensen distance measure and flexible beta linkages method with  $\beta=-0.25$ , using the computer program PC-ORD 5.0 (McCune and Mefford 2006). Indicator species analysis was used to prune the dendrogram and optimize the number of clusters (McCune and Grace 2002). We averaged p-values across all species for each cluster level using Monte Carlo Analysis and the cluster level with the lowest average p-value was used as the optimal level. Ordination of vegetation, soil and water chemistry, and environmental variables was conducted using Nonmetric Multidimensional Scaling (NMS) in PC-ORD 5.0 using Sørensen distance measure and 3-axes, as determined by the stress test (McCune and Grace 2002).

### Disturbances and Restoration Potential

We identified disturbances on aerial imagery, topographic maps, and during site visits. The level of severity of each disturbance was assessed by the proportion of fen it impacted and the intensity of the impact. Disturbances were ranked by severity, those that impacted <1% of the fen were ranked as low, 1–5% as moderate, 5–15% as high, and >15% as very high. We also assessed hydrologic disturbances, including headcuts, gullies, ditches, diversions, and road cuts to fens by estimating the proportion of area that was altered. Vegetation disturbance was assessed by identifying the proportion of bare soil or the presence of invasive or non-wetland plant species, and the degree of grazing or browsing. Soil disturbance was the proportion of fen with bare soil, mineral material overlying peat soil, or undergoing erosion.

We assessed each site's restoration priority as very high, high, low, or very low based on the likely ease or difficulty of restoration and the rarity or commonness of the fen type. Sites considered high or very high restoration priorities could easily be restored or were rare fen types. Sites rated as low or moderate restoration priority were slightly impacted or so severely impacted that restoration would be cost prohibitive.

## Results

### Mapping

We preliminarily identified 624 sites as fens on aerial imagery in the 37 study watersheds (Fig. 1). Our field surveys indicate that our delineation had an accuracy of 92% for correctly identifying polygons that were fens. We altered boundaries on a number of polygons in the field, and a few polygons were added. We estimate that

approximately 10% of fens were missed in the image based delineation. Mapped sites ranged from 0.2 to 20.5 ha in area, with a mean of 1.2 ha and a median of 0.8 ha. Site elevations ranged from 2,532 to 3,832 m. Approximately 90% of fens occurred above 3,000 m elevation, with an average elevation of 3,288 m (Fig. 2a).

### Physical and Chemical Characteristics

We visited 182 fens (30% of all mapped fens) and analyzed 309 homogenous stands in these fens (Fig. 1). Mean peat thickness was 1.25 m (std=0.78) and ranged from 0.40 to >4.00 m. We likely underestimated the thickest peat bodies because our soil probe was 4 m long. Mean soil organic matter content was 60% (std=15%), which is approximately 30% organic carbon (Chimner unpublished data). Peat

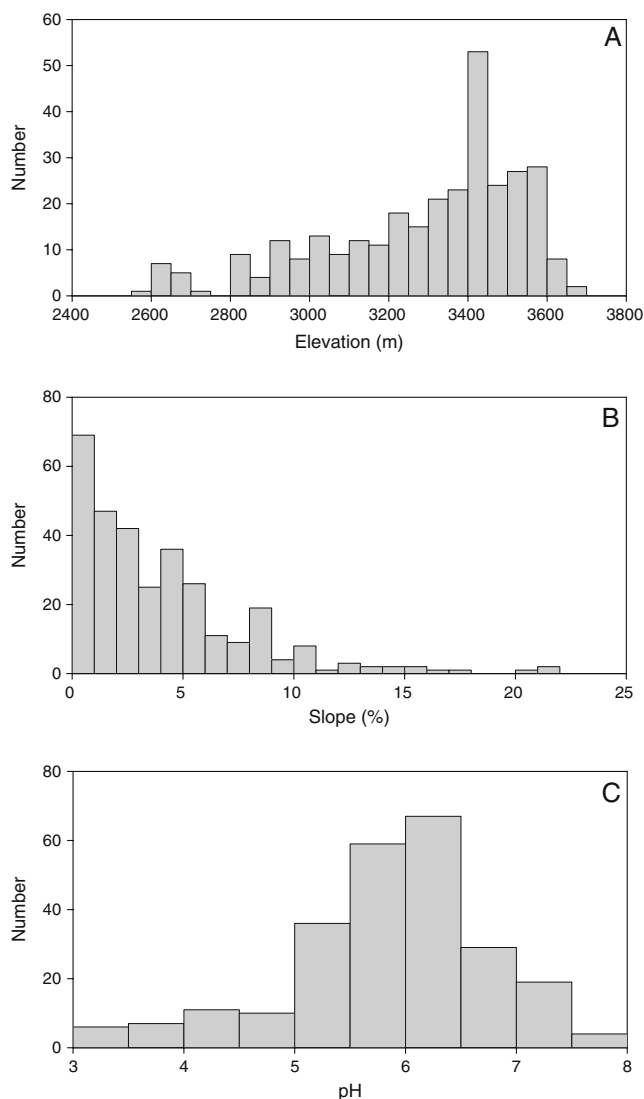
decomposition, as indicated by the von Post scale, averaged 5, moderately decomposed, with *Sphagnum* peat being least decomposed and drained *Carex* peat the most decomposed. Approximately 28% of fens had formed in depression landforms and 78% on slopes. The mean fen slope was 5% and the maximum 21% (Fig. 2b).

Groundwater pH in most fens ranged from 5.0 to 6.5; although, several fens were basic with pH>7.0 and a number were highly acid with pH<4.5 (Fig. 2c). Groundwater pH varied due to watershed bedrock composition and surficial deposit geochemistry (Table 1). Watersheds with some calcareous bedrock had the highest concentrations of Ca<sup>+2</sup>, Mg<sup>+2</sup>, and Na<sup>+</sup> in ground water. Intrusive igneous watersheds had the highest concentrations of K<sup>+</sup>, while volcanic watersheds had high Fe<sup>+3</sup>.

### Vegetation

We identified 188 vascular and 63 bryophyte species in the study plots (Supplementary Material, Appendix A). A total of 30 species of *Carex* were found (34 in Cyperaceae) and ~80% of the stands were *Carex*-dominated (>50% cover). *Carex aquatilis* was the most common species found, occurring in 65% of plots. *Rhynchospora alba* was found in one fen, and this genus was not previously known for the Rocky Mountains south of Idaho (Flora of North America Editorial Committee 2002). Unlike many regions with peatlands (Rydin and Jeglum 2006), fens in the Rockies have little tree cover (Johnson 1996). Only 5% of the study fens supported any trees, and only one species, *Picea engelmannii*, commonly occurred in fens. Most of the forested fens analyzed occurred at the margins of large fen complexes. Many fens were shrub covered. However, instead of species in the family *Ericaceae*, as is common in most boreal peatlands, southern Rocky Mountain fens are covered by six species of *Salix*, with *Salix planifolia* being most common. Bryophyte cover and diversity was dominated by mosses in the family Amblystegiaceae with 18 species and *Warnstorfia fluitans* was the most common member of this family. Other common brown mosses included *Aulacomnium palustre*, *Ptychostomum pseudotriquetrum*, and *Climacium dendroides*.

Hierarchical cluster analysis separated the 309 stands into 20 community types (Table 2). The communities are divided into three main groups based on geochemistry (rich, intermediate, and iron fens) and secondarily divided into the hydrogeomorphic classes of sloping and depressional fens (Table 2). We classified vegetation communities with an average pH >6.5 as rich fens. These communities generally also had high ground water Ca<sup>+2</sup> and Mg<sup>+2</sup> concentrations, although there were a few with lower concentrations. Fens with pH between 5 and 6.5 were classified as intermediate fens and had low Ca<sup>+2</sup> and Mg<sup>+2</sup>



**Fig. 2** Histograms of **a** mapped fen elevations, **b** fen slopes, and **c** fen pH



**Table 1** Mean ( $\pm$ se) water chemistry (mg/L) of ground water by dominant watershed rock type

Cation	Calcareous (n=56)	Volcanic (n=156)	Intrusive Igneous (n=54)
Ca <sup>+2</sup>	70.7 $\pm$ 7.7 <sup>a</sup>	32.6 $\pm$ 3.4 <sup>b</sup>	6.0 $\pm$ 0.9 <sup>c</sup>
Mg <sup>+2</sup>	9.1 $\pm$ 1.1 <sup>a</sup>	6.0 $\pm$ 0.1 <sup>b</sup>	1.1 $\pm$ 0.4 <sup>c</sup>
K <sup>+</sup>	1.6 $\pm$ 0.1 <sup>a</sup>	1.2 $\pm$ 0.1 <sup>a</sup>	5.0 $\pm$ 1.2 <sup>b</sup>
Na <sup>+</sup>	4.9 $\pm$ 0.5 <sup>a</sup>	3.2 $\pm$ 0.3 <sup>b</sup>	0.91 $\pm$ 0.1 <sup>c</sup>
Fe <sup>+3</sup>	0.1 $\pm$ 0.1 <sup>a</sup>	0.4 $\pm$ 0.1 <sup>b</sup>	0.1 $\pm$ 0.1 <sup>a,b</sup>

Letters denote significant difference ( $P < 0.05$ ) between watershed types as tested by ANOVA using Tukey's post-hoc test

concentrations. Fens with low pH (<5) in the study area were iron fens, not ombrotrophic bogs, and occurred in watersheds with outcroppings of highly mineralized iron pyrite that oxidizes to form sulfuric acid, creating ground water with naturally low pH but high Ca<sup>+2</sup> and Mg<sup>+2</sup> concentrations. The majority of fens in our study were intermediate fens (66% of total fens sampled), followed by rich fens (23%) with iron fens being rare (1%).

**Table 2** Plant community types grouped by geochemistry (rich, intermediate, and iron) and landform (sloping and depression)

Group	Plant Community
Rich Fens:	
Sloping Rich Fens	
1.1:	<i>Salix monticola/Alnus incana</i>
1.2:	<i>Salix wolfii/Pentaphylloides floribunda</i>
1.3:	<i>Carex buxbaumii/Eriophorum angustifolium</i>
1.4:	<i>Eriophorum angustifolium/Juncus albescens</i>
1.5:	<i>Psychrophila leptosepala/Primula parryi</i>
Depression Rich Fens	
2.1:	<i>Carex utriculata/Galium trifidum</i>
2.2:	<i>Carex magellanica/Carex utriculata</i>
2.3:	<i>Carex limosa/Menyanthes trifoliata</i>
Intermediate Fens:	
Sloping Intermediate Fens	
3.1:	<i>Picea engelmannii/Calamagrostis canadensis</i>
3.2:	<i>Salix planifolia/Carex aquatilis</i>
3.3:	<i>Eleocharis quinqueflora/Carex aquatilis</i>
3.4:	<i>Carex illota/Pedicularis groenlandica</i>
3.5:	<i>Carex aquatilis/Psychrophila leptosepala</i>
3.6:	<i>Carex aquatilis/Pedicularis groenlandica</i>
3.7:	<i>Carex saxatilis/Scorpidium cossonii</i>
3.8:	<i>Eleocharis quinqueflora/Warnstorfia fluitans</i>
Depression Intermediate Fens	
4.1:	<i>Carex canescens/Calamagrostis canadensis</i>
4.2:	<i>Carex lasiocarpa/Drosera anglica</i>
Iron Fens:	
5.1:	<i>Betula glandulosa/Sphagnum russowii</i>
5.2:	<i>Carex aquatilis/Sphagnum fimbriatum</i>

Community types named by a combination of dominant species and indicator species

The most common species in iron fens were *Betula glandulosa*, *Carex aquatilis*, and a continuous carpet of *Sphagnum* mosses. Ten species of *Sphagnum* were identified in iron fens including *S. obtusum*, which was not been previously known for the Rocky Mountains (Andrus personal communication). We also found additional populations of another rare peat moss *Sphagnum balticum*, which is disjunct from its main range in boreal regions of Canada (Cooper et al. 2002). The most common *Sphagnum* species were *S. russowii*, *S. fimbriatum*, and *S. angustifolium*.

More intermediate fen communities (10) than rich fen communities (8) or iron fen communities (2) occur in the study area, and more sloping fen (14) than depression fen (6) community types occur (Table 2). Sloping fens had higher total vascular and bryophyte species richness and diversity than depression fens, but there was little difference between rich sloping fens and intermediate sloping fens, or between rich depression fens and intermediate depression fens (Table 3). Iron fens had the lowest number of total and vascular species, although many of their species are regionally rare.

Multivariate Nonmetric Multidimensional Scaling (NMS) analysis had a 3-dimensional solution of 21.45 and a final instability 0.0038 (Fig. 3). Axis 1 had an  $r^2$  of 0.19 and was most correlated to elevation ( $r^2=0.29$ ) and Ca<sup>+2</sup> concentrations in ground water ( $r^2=0.14$ ; Table 4). Axis 2 had an  $r^2$  of 0.18 and was most correlated with elevation ( $r^2=0.15$ ) and slope ( $r^2=0.12$ ). Axis 3 had an  $r^2$  of 0.16 and was most correlated with pH ( $r^2=0.17$ ).

### Disturbance and Restoration Potential

Forty-two (23%) of the fens visited had some level of disturbance. The most severe disturbances were from ditching, mining, urban development, and roads, with roads being the most common disturbance (Table 5). The least severe disturbances were from native animal use (e.g., elk wallows) and recreational uses (e.g., skiing, biking). Disturbances impacted vegetation, hydrological functions, soil stability, or all three.

Five fens were classified as having very high restoration priority and 13 additional fens as having a high restoration priority (data not shown). Six fens classified as having high or very high restoration priority were rare iron fens (out of

**Table 3** Total number of species (T) present and Simpsons Diversity Index (D) of major fen vegetation types. Separated by all species, vascular species and bryophytes

	All		Vascular		Bryophyte	
	T	D	T	D	T	D
1-Rich Sloping	149	0.54	124	0.55	25	0.51
2-Rich Depression	75	0.15	57	0.15	18	0.17
3-Intermediate Sloping	155	0.59	122	0.57	33	0.66
4-Intermediate Depression	72	0.13	54	0.12	18	0.15
5 Iron Fen	54	0.13	36	0.11	18	0.19

15 iron fens surveyed). Nineteen fens were ranked as medium and the remaining 145 fens as low restoration priority. All but one of the low restoration priority fens were in good or excellent condition and did not require restoration. However, one fen was in poor condition from a highway bisecting it and was ranked as low restoration priority due to the cost of restoration. Common disturbances ranked as having high or very high restoration priorities were from small roads, mining, and ditching. However, some fens with severe disturbance from roads or mining were ranked as medium or low restoration priorities due to the high cost of restoration required to fix these sites.

**Discussion**

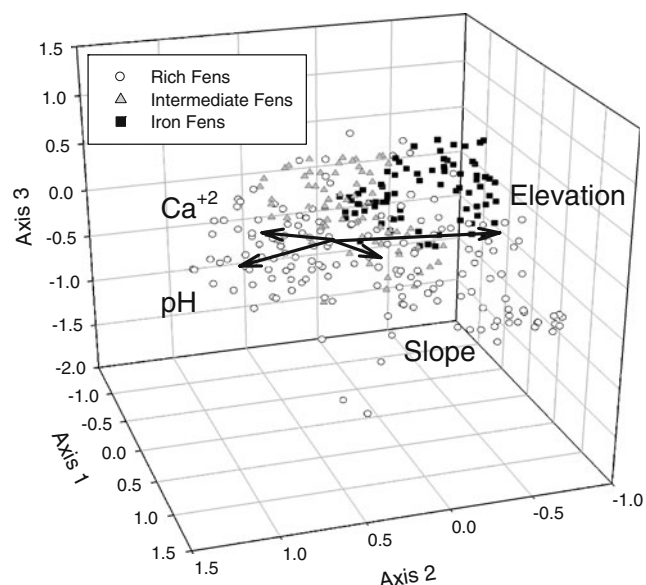
Mountain Fen Characteristics

We estimate that approximately 2,000 fens occur in the subalpine zone (~3,000–4,000 m) of the San Juan Mountains,

covering 2,400 ha, or 1% of area. Few studies have estimated fen abundance on the scale of an entire mountain region, but information from this and other studies indicate that fens are numerous in mountain regions of western North American (Chadde et al. 1998; Cooper and Wolf 2006; Lemly 2007; Patterson and Cooper 2007).

Mountain peatlands also occur along the entire length of the Andes, and in tropical and subtropical regions including the páramo of Colombia, Venezuela, and Ecuador (Samaniego et al. 1998; Chimner and Karberg 2008); the puna in Chile, Peru, and Bolivia (Preston et al. 2003; Earle et al. 2003; Cooper et al. 2010); central Andes and Patagonia (Coronato et al. 2006; Chimner et al. 2007); and Tierra del Fuego where peatlands cover large areas (Kleinebecker et al. 2008). Mountain peatlands also occur in other temperate mountain ranges including the Alps, Himalayas, in Japan, and the Southern Alps of New Zealand (Gerdol 1995; Wahren et al. 2001; Dickinson et al. 2002; Chen et al. 2008; Koch et al. 2008; Fujita et al. 2009), as well as Hawaii, Africa and Indonesia (Islebe et al. 1996; Chimner 2004).

Fens in mountain regions are typically small in size because they are limited by steep slopes and the small size of watersheds supporting them (Patterson and Cooper



**Fig. 3** NMS diagram of stands and environmental vectors grouped by wetland type

**Table 4** Pearson ( $r^2$ ) and Kendall ranked (tau) correlations of environmental values with ordination axes

	Axis 1		Axis 2		Axis 3	
	$r^2$	tau	$r^2$	tau	$r^2$	tau
Elevation	0.29	0.39	0.15	-0.21	0.07	0.18
Slope	0.00	0.02	0.12	-0.29	0.01	-0.04
Water table	0.03	-0.18	0.01	-0.08	0.04	-0.25
von Post	0.01	-0.07	0.01	0.05	0.10	-0.23
Peat thickness	0.00	-0.04	0.01	0.05	0.01	0.09
pH	0.03	0.05	0.06	0.19	0.17	-0.28
calcium	0.14	-0.33	0.06	0.15	0.04	-0.24
magnesium	0.03	-0.24	0.08	0.18	0.08	-0.22
potassium	0.02	-0.05	0.00	-0.05	0.00	0.02
sodium	0.12	-0.35	0.04	0.11	0.04	-0.16
iron	0.02	0.02	0.02	-0.05	0.00	0.05

**Table 5** Disturbance categories, number of times disturbance was encountered during field surveys, and average severity level of disturbance (1 = lowest severity and 5 = most severe impact)

Disturbance	Number of occurrences	Average severity
Drainage	7	3.9
Mining	21	3.2
Other	6	2.8
Development	19	2.6
Roads	52	2.4
Grazing	10	2.2
Native animals	23	1.8
Recreation	21	1.7

Categories ranked by average severity

Numbers are based on stand level data and each site can have more than one disturbance

2007). The average fen in our study was 1.2 ha in area, which is similar to fen size in other mountain ranges in the western U.S., with the largest fens generally being less than 100 ha (Cooper and Wolf 2006; Lemly 2007).

Mountain fen peat bodies are relatively thin, averaging 1–1.25 m thick in the Rockies and Sierra Nevada (Cooper and Wolf 2006; Lemly 2007; this study, Chimner unpublished data). However, some mountain peatlands are >4 m in the Rocky Mountains, and >7 m in the Peruvian Andes (Cooper et al. 2010). Mountain fen soils typically have high mineral and low organic carbon content (Chimner and Karberg 2008). Soils from 419 Colorado fens average 30% organic carbon (60% soil organic matter) (this study, Chimner unpublished data), which is similar to the carbon content of Sierra Nevada fen soils (Cooper and Wolf 2006). However, carbon accumulation rates can be quite high in mountain fens because soil bulk density is typically high (Chimner et al. 2002).

Bogs do not occur in our study area. Mountain bogs occur only in mountain ranges with a hypermaritime climate (e.g., coastal areas of British Columbia, Canada, and southeastern Alaska) that receive ample rain and have high humidity throughout the year (Asada et al. 2003). Mountain regions with dry summers (e.g., Rockies and Sierra Nevada) have fens (Cooper and Andrus 1994; Cooper and Wolf 2006; Lemly 2007). Because most mountain fens are sloping and supported by ground-water discharge, watershed geology exerts a strong influence in ground-water chemical content (Vitt and Chee 1990; Cooper and Andrus 1994; Bedford and Godwin 2002; Bragazza et al. 2003), which strongly influences fen plant community composition (Vitt and Chee 1990; Cooper and Andrus 1994; Cooper 1996; Bedford and Godwin 2002; Bragazza et al. 2003). Hydrogeomorphic landform can also control fen plant community composition (Bridgman et al.

1996; Grootjans et al. 2006). We used well known geochemical fen categories to organize the plant communities into rich, intermediate, and iron fen types. Intermediate fens are common on granite and other intrusive igneous watersheds while rich fens are common in districts with calcareous rocks (e.g., limestone and dolomite) and iron fens are present where iron pyrite rich rocks outcrop (Cooper and Andrus 1994; Cooper 1996; Cooper et al. 2002).

#### Disturbances and Fen Restoration

Ten percent of the fens sampled were highly disturbed, and were ranked as having high to very high restoration priorities, indicating that a large number of fens in the San Juan Mountains are in need of restoration. The most common disturbance encountered was roads, which are present in most study watersheds. Roads impact fens by intercepting water flow, bisecting fens, and are commonly a source of mineral sediment that can bury organic soils. Most roads had limited impacts to fens, but a few roads have caused severe impacts, especially where poor culvert placement created channels and erosion. Several fens also showed signs of off-road vehicles driving through or adjacent to them causing erosion.

Many fens were impacted by development other than roads (e.g., golf courses, parking structures, ski runs and structures), especially around the towns of Mountain Village and Telluride. The main impact from these developments was filling or structures that altered ground-water flow supporting fens.

Several fens had drainage ditches or water diversions. Dewatering is a severe disturbance in fens because it lowers the water table allowing peat to oxidize and the ground surface to subside due to increased decomposition (Chimner and Cooper 2003a).

Invasive species and heavy livestock grazing were minor issues. The few non-native species found, including *Breca arvensis*, *Descurainia sophia*, *Taraxacum officinale*, and *Trifolium repens* occurred in the dried and disturbed portions of a few fens. Relatively little domestic livestock grazing occurs in the study area at present and impacts were minor compared to grazing impacts in other mountain regions (Dull 1999; Preston et al. 2003; Cooper and Wolf 2006; Cooper and Wolf 2006; Chimner et al. 2007). We also found disturbances from native animals, primarily elk wallows and trampling, which caused erosion and gulling.

Two fen types were most likely to be highly disturbed and in need of restoration. Iron fens, which are rare in the western U.S., were frequently in poor condition with 6 out of 15 iron fens surveyed requiring restoration. Metal mines were often located near iron fens, which were used as tailings dumps. Besides the physical factor of tailings covering peat, tailing piles can disrupt surface and

ground-water flow and alter chemical and mineral sediment influx into fens. Some iron fens have been mined for “bog iron ore”, which left the fen completely denuded even a century later, with bare soils undergoing severe frost heave and erosion.

Stands of rich sloping fens dominated by *Eleocharis quinqueflora* were disturbed in many areas, and their string and flank patterns and “step-terraces” were eroded by off road vehicles, horses, or elk. Most sites undergoing gully erosion were of this community type.

In summary, fens are an important component of subalpine zone ecosystems in the San Juan Mountains. However, the role mountain fens play in regional water and carbon cycles, and the provision of local and regional habitat for plants and animals is largely unknown (Vitt et al 2001; Bedford and Godwin 2002). Most mountain fens occur on slopes supported by ground-water discharge, which makes them especially vulnerable to disturbances that intercept ground water, for example roads and ditches, or cause erosion, for example mining, vehicle travel, and trampling. Iron fens and *E. quinqueflora* dominated fens are most likely to need protection and restoration.

**Acknowledgements** This research was funded by two Wetland Program Development grants from EPA Region 8. We would like to thank landowners, especially the San Juan National Forest, for help in conducting this project. We thank Kerry Cutler, Krista Northcott, Erin Hagland and Adam Birken for help with GIS and field assistance and three anonymous reviewers for improving this manuscript.

## References

- Asada T, Warner BG, Pojar J (2003) Environmental factors responsible for shaping an open peatland-forest complex on the hypermaritime north coast of British Columbia. *Canadian Journal of Forest Research* 33:2380–2394
- Bedford B, Godwin K (2002) Fens of the United States: distribution, characteristics, and scientific connection vs. legal isolation. *Wetlands* 23:608–629
- Belyea LR, Warner BG (1996) Temporal scale and the accumulation of peat in a Sphagnum bog. *Canadian Journal of Botany* 74:366–377
- Bragazza L, Gerdol R, Rydin H (2003) Effects of mineral and nutrient input on mire bio-geochemistry in two geographical regions. *Journal of Ecology* 91:417–426
- Bridgham SD, Pastor P, Janssens JA, Chapin C, Malterer TJ (1996) Multiple limiting gradients in peatlands: a call for a new paradigm. *Wetlands* 16:45–65
- Brinson MM (1993) A hydrogeomorphic classification for wetlands. US Army Corps of Engineers Waterways Experiment Station, Vicksburg, Wetlands Research Technical Report WRP-DE-4
- Chadde SW, Shelly JS, Bursik RJ, Moseley RK, Evenden AG, Mantas M, Rabe F, Heidel B (1998) Peatlands on national forests of the northern Rocky Mountains: ecology and conservation. USDA Forest Service, Rocky Mountain Research Station, Ogden, p 75, Gen. Tech. Rep. RMRS-GTR-11
- Chen H, Yao SP, Wu N, Wang YF, Luo P, Tian JQ, Gao YH, Sun G (2008) Determinants influencing seasonal variations of methane emissions from alpine wetlands in Zoige Plateau and their implications. *Journal of Geophysical Research-Atmospheres* 113:D12303. doi:10.1029/2006JD00807
- Chimner RA (2004) Soil respiration rates in tropical peatlands of Micronesia and Hawaii. *Wetlands* 24:51–56
- Chimner RA, Cooper DJ (2002) Modeling carbon accumulation in Rocky Mountain fens. *Wetlands* 22:100–110
- Chimner RA, Cooper DJ (2003a) Carbon balances of pristine and hydrologically modified southern Rocky Mountain fens. *Canadian Journal of Botany* 81:477–491
- Chimner RA, Cooper DJ (2003b) Influence of water table levels on CO<sub>2</sub> emissions in a Colorado subalpine fen: an in situ microcosm study. *Soil Biology and Biochemistry* 35:345–351
- Chimner RA, Karberg J (2008) Long-term carbon accumulation in two tropical mountain peatlands, Andes Mountains, Ecuador. *Mires and Peat* 3: Art. 4
- Chimner RA, Cooper DJ, Parton WJ (2002) Modeling carbon accumulation in Rocky Mountain fens. *Wetlands* 22:100–110
- Chimner RA, Brione E, Bonvissuto G, Cremona M (2007) Exploring the hydro-ecological conditions of high elevation wetlands in the Andes Mountains. Final report to The National Geographical Society. 38 pages
- Clausen JC, Ortega IM, Glaude CM, Relyea RA, Garay G, Guineo O (2006) Classification of wetlands in a Patagonian National Park, Chile. *Wetlands* 26:217–229
- Cooper DJ (1996) Soil and water chemistry, floristics and phytosociology of the extreme rich High Creek Fen, South Park, Colorado. *Canadian Journal of Botany* 74:1801–1811
- Cooper DJ, Andrus R (1994) Peatlands of the west-central Wind River Range, Wyoming: vegetation, flora and water chemistry. *Canadian Journal of Botany* 72:1586–1597
- Cooper DJ, Wolf E (2006) Fens of the California Sierra Nevada: landforms, geochemistry, vegetation, and influences of livestock grazing. Report to U.S. Forest Service, Vallejo, p 65
- Cooper DJ, MacDonald LH, Wenger SK, Woods SW (1998) Hydrologic restoration of a fen in Rocky Mountain National Park, Colorado, USA. *Wetlands* 18:335–345
- Cooper DJ, Andrus RA, Arp CD (2002) *Sphagnum balticum* in a Southern Rocky Mountains iron fen. *Madrono* 49:186–188
- Cooper DJ, Wolf EC, Colson C, Vering W, Granda A, Meyer M (2010) Wetlands of the Minas Congas Region, Cajamarca, Peru. *Arctic, Antarctic and Alpine Research* 42:19–33
- Coronato A, Roig C, Collado L, Roig F (2006) Geomorphologic emplacement and vegetation characteristics of Fuegian peatlands, southernmost Argentina, South America. In: Martini IP, Cortizas AM, Chesworth W (eds) Peatlands: evolution and records of environmental and climate changes. Elsevier, Netherlands, pp 111–128
- Dickinson KJM, Chague-Goff C, Mark AF, Cullen L (2002) Ecological processes and trophic status of two low-alpine patterned mires, south-central South Island, New Zealand. *Austral Ecology* 27:369–384
- Dull RA (1999) Palynological evidence for 19th century grazing-induced vegetation change in the southern Sierra Nevada, California, USA. *Journal of Biogeography* 26:899–912
- Earle LR, Warner BG, Aravena R (2003) Rapid development of an unusual peat-accumulating ecosystem in the Chilean Altiplano. *Quaternary Research* 59:2–11
- ESRI (2006) ArcView 9.2. Environmental Systems Research Institute, Inc, Redlands
- Flora of North America Editorial Committee (2002) Flora of North America, Volume 23 Magnoliophyta: Commelinidae (in part): Cyperaceae. Oxford University, New York, 608p
- Fujita H, Igarashi Y, Hotes S, Takada M, Inoue T, Kaneko M (2009) An inventory of the mires of Hokkaido, Japan—their development, classification, decline, and conservation. *Plant Ecology* 200:9–36



- Kleinebecker T, Hölzel N, Vogel A (2008) South Patagonian ombrotrophic bog vegetation reflects biogeochemical gradients at the landscape level. *Journal of Vegetation Science* 19:151–160
- Koch O, Tscherko D, Kupperts M, Kandeler E (2008) Interannual ecosystem CO<sub>2</sub> dynamics in the alpine zone of the Eastern Alps, Austria. *Arctic Antarctic and Alpine Research* 40:487–496
- Gerdol R (1995) Community and species-performance patterns along an alpine poor-rich mire gradient. *Journal of Vegetation Science* 6:175–182
- Grootjans AP, Adema EB, Bleuten W, Joostn H, Madaras M, Janakova M (2006) Hydrological landscape settings of base-rich fen mires and fen meadows: an overview. *Applied Vegetation Science* 9:175–184
- Islebe GA, Hooghiemstra H, Van't Veer R (1996) Holocene vegetation and water level history in two bogs of the Cordillera de Talamanca, Costa Rica. *Vegetatio* 124:155–171
- Johnson JB (1996) Phytosociology and gradient analysis of a subalpine treed fen in Rocky Mountain National Park, Colorado. *Canadian Journal of Botany* 74:1203–1218
- Lemly JM (2007) Fens of Yellowstone National Park, USA: regional and local controls over plant species distribution. Thesis. Colorado State University, Ft. Collins, CO., USA
- Maxwell JR, Edwards CJ, Jensen ME, Paustian S, Parrott H, Hill D (1995) A hierarchical framework of aquatic ecological units in North America (Nearctic Zone). General Technical Report NC-GTR-176. Department of Agriculture, Forest Service, North Central Forest Experiment Stations, St. Paul, MN
- McCune B, Grace JB (2002) Analysis of ecological communities. MjM Software Design, Gleneden Beach, OR
- McCune B, Mefford MJ (2006) PC-ORD. Multivariate analysis of ecological data, version 5.18. MjM Software, Gleneden Beach, OR
- McQueen CR, Andrus RE (2007) *Sphagnum-Sphagnaceae*. In: Flora of North America Editorial Committee (eds) Flora of North America North of Mexico. Vol. 27: Bryophytes: Mosses, Part 1. Oxford University Press, New York
- Millennium Ecosystem Assessment (2005) Ecosystems and human well-being. Published by Island Press. ISBN 1559632283, 9781559632287
- Mueller-Dombois D, Ellenberg H (1974) Aims and methods of vegetation ecology. Wiley, New York, p 547
- National Institute of Invasive Species Science (NIISS) (2006) EcoNab Database. Available for download at <http://www.niiss.org/cwis438/gather/FieldTools.php>. Downloaded for this project in June 2006
- Patterson L, Cooper DJ (2007) The use of hydrologic and ecological indicators for the restoration of drainage ditches and water diversions in a mountain fen, Cascade Range, California. *Wetlands* 27:290–304
- Preston D, Fairbairn J, Paniagua N, Maas G, Yevara M, Beck S (2003) Grazing and environmental change on the Tarija Altiplano, Bolivia. *Mountain Research and Development* 23:141–148
- Rydin H, Jeglum JK (2006) The biology of peatlands. Oxford University, USA, p 360
- Samaniego P, Monzier M, Robin C, Hall ML (1998) Late Holocene eruptive activity at Nevado Cayambe Volcano, Ecuador. *Bulletin of Volcanology* 59:451–459
- Schimel DS, Braswell BH (2005) The role of mid-latitude mountains in the carbon cycle: Global perspective and a Western U.S. case study. p. 1–8. In: Huber U. M., H. K. M. Bugmann and M. A. Reasoner (eds.) *Global Change and Mountain Regions: An Overview of Current Knowledge*. Springer-Verlag
- Soil Survey Staff (2006) Keys to soil taxonomy, Tenth Edition. U.S. Department of Agriculture, Natural Resources Conservation Service, Washington D.C.
- Tiner RW, Bergquist HC, DeAlessio GP, Starr MJ (2002) Geographically isolated wetlands: a preliminary assessment of their characteristics and status in selected areas of the United States. U.S. Department of the Interior, Fish and Wildlife Service, Northeast Region, Hadley
- Wahren CHA, Williams RJ, Papst WA (2001) Vegetation change and ecological processes in alpine and subalpine *Sphagnum* bogs of the Bogong High Plains, Victoria, Australia. *Arctic Antarctic and Alpine Research* 33:357–368
- Weber WA (2003) The Middle Asian element in the Southern Rocky Mountain Flora of the western United States: a critical biogeographical review. *Journal of Biogeography* 30:649–685
- Weber WA, Wittmann RC (2001) Colorado Flora, Western Slope, 3rd edn. University Press of Colorado, Colorado, p 488
- Weber WA, Wittmann RC (2007) Bryophytes of Colorado: mosses, liverworts, and hornworts. Pilgrims Process, Inc. Boulder, CO
- Winters D, Bohn B, Cooper DJ, Eaglin G, Hamerlink J, Hirsch C, Poff NL, Quimby C, Rahel F, Scaife D, Staley D, Welker M, Wohl E (2003) Conceptual framework and protocols for conducting broad scale aquatic, riparian, and wetland ecological assessments. U.S. Department of Agriculture, Forest Service, Rocky Mountain Region, Lakewood, p 147
- Wohl E, Cooper DJ, Poff L, Rahel F, Staley D, Winters D (2007) Assessment of stream ecosystem function and sensitivity in the Bighorn National Forest, Wyoming. *Environmental Management* 40:284–302
- Vitt DH, Chee WL (1990) The relationships of vegetation to surface water chemistry and peat chemistry in fens of Alberta, Canada. *Vegetatio* 89:87–106
- Vitt DH, Halsey LA, Campbell C, Bayley SE, Thormann MN (2001) Spatial patterning of net primary production in wetlands of continental western Canada. *Ecoscience* 8:499–505
- Viviroli D, Weingartner R, Messeril B (2003) Assessing the hydrological significance of the world's mountains. *Mountain Research and Development* 23:32–40
- Zier JL, Baker WL (2006) A century of vegetation change in the San Juan Mountains, Colorado: an analysis using repeat photography. *Forest Ecology and Management* 228:251–262